Report No. CG-D-21-94

AD-A285 871

Survey of Robotic Tankship Inspection Technology

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NOV 0 2 1994

FINAL REPORT
FEBRUARY 1994

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Prepared for:

U.S. Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

and

U.S. Department of Transportation
United States Coast Guard
Office of Engineering, Logistics, and Development
Washington, DC 20593-0001

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-21-94		

4. Title and Subtitle	5. Report Date
Survey of Robotic Tankship Inspection Technology	February 1994
	6. Performing Organization Code
7. Author(s) J.M. Alzheimer	8. Performing Organization Report No. R&DC 06/94
9. Performing Organization Name and Address Battelle Pacific Northwest Laboratories Richland, WA 99352	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. Z51100-2-E-00690
	13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, Connecticut 06340-6096 Department of Transportation U.S. Coast Guard Office of Engineering, Logistics, and Development Washington, D.C. 20593-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Arrangements for a copy of the robotic inspection concept inside a VLCC wing tank computer simulation can be made through the U.S. Coast Guard Research and Development Center's Marine Engineering Branch.

16. Abstract

Current tankship inspection techniques are manual, time consuming, and dangerous. Tankships are difficult to thoroughly inspect due to the constraints imposed by limited time available for inspections, the size of the vessel, and the inability to access the upper areas of large tank spaces. Robotic inspection systems applied to the inspection of tankships could provide a more complete examination of structural details, require less tank preparation if manned entry were not needed, and improve inspector safety.

This report provides industry and parties interested in exploring the feasibility of some new or existing robotic technology with guidance for possible design or adaptation of remote inspection systems for tankship use. Although robotic technology is utilized in many other applications, significant technology development and testing must occur before the inspection of tankships can be carried out completely with robotic/remote inspection systems. Many parts of the inspections will still have to be done with a man-in-the-tank for the foreseeable future. Progress is needed in the development of deployment systems, vision systems, operator interfaces, and long reach manipulator stability before a system can be produced that is viable for routine use.

17. Key Words	18. Distribution Statement
robotic tankship vessel inspection	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. SECURITY CLASSIF. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

METRIC CONVERSION FACTORS

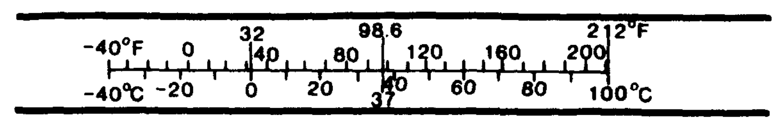
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The inspections of merchant vessel tank internal structures are currently performed using primarily hands-on, in-the-tank methods. However, the amount of time and effort required to prepare the tanks for man-in-the-tank inspections are significant. In addition, the huge volumes and distances involved make accessing all but the lower parts of the tanks difficult and dangerous, and limit the effectiveness of the method.

The objective of the Survey of Robotic Tankship Inspection Technology project was to perform a technical industry survey and evaluate promising robotic technology for the inspection of merchant vessel internal tank structures. The project had three tasks. The first task was the development of general performance requirements for remote robotic inspection of merchant vessel tankships. The second task was an industry survey of remote inspection technology applicable to tankship inspections. The third task was the development of a computer simulation of a robotic system design concept inside a typical ship tank.

The incentives for using robotic devices to inspect tankship internal structures are related to the potentials for more thorough inspections, reduced costs, and improved operator safety.

The development of the general performance requirements was based upon the review of typical tankship drawings, a visit to the U.S. Coast Guard (USCG) Marine Safety Office in Portland, Oregon with tours of typical tankships, and contacts with shipping companies and classification societies. The general performance requirements considered the types of defects that need to be located and characterized, the characteristics of typical tank internal structures such as geometry, surface conditions and lighting, safety aspects of the tankship environment, and operational characteristics such as setup, speed of inspection and ease of use.

The industry survey of remote inspection technology utilized a computer- based literature search, review of literature related to long reach robotic manipulators considered for inspection and cleanup of underground storage tanks, review of literature related to remote inspection of nuclear facilities, and leads generated as a result of contacts with shipping companies and classification societies.

No existing robotic inspection systems were identified during the industry survey that met the general performance requirements. The robotic inspection of tankship internal structures has a very unique combination of requirements imposed by the structures to be inspected, the hazardous environment, and the desire for a man-portable system. Of all the inspection systems located, only two were specifically designed for tankship inspections. Neither of these systems could be considered capable of meeting the general performance requirements. One of these is a remotely-piloted submersible vehicle that operates in a water-filled tank, and the other is an inverted periscope system inserted through the deck to perform visual inspections of under deck structures. Additional inspection systems not specifically designed for tankship inspections were found that had some of the required

characteristics. Although none of these latter systems could be used in their current configurations, they represent technology that could be adapted to the inspection of tankships.

None of the inspection systems found were adequate for all aspects of tankship inspections. While some progress is being made in the area of remote inspection of tankships, none of the currently available systems would fulfill more than a rather small subset of the performance requirements.

Based on the author's understanding of the requirements of tankship inspections and the foreseeable capabilities of robotic technology, concepts for developments in remote inspection systems are discussed along with the possible benefits of such systems.

The original intent was to develop an animated, 3-D computer graphics model of the most promising robotic tankship inspection system. No systems were found capable of robotic tankship inspections. Therefore, a conceptual model of a system was developed. This model was based only on reach and dexterity requirements and is considered useful in demonstrating potential inspection sequence. No considerations were given to weight and strength constraints during development of the conceptual model. This model, while useful in helping to better understand the application of robotics to tankship inspections, should not be considered to represent a viable design. The development of a viable robotic inspection system for this application would require that all aspects of the general performance requirements be satisfied.

1.0 INTRODUCTION

This report presents the work conducted on the "Survey of Robotic Tankship Inspection Technology" project for the U. S. Coast Guard Research and Development Center in Groton, Connecticut. The work was performed by staff in the Robotics and Mechanical Systems Group in the Automation and Measurement Sciences Department at the Pacific Northwest Laboratory (PNL) operated for the U. S. Department of Energy by Battelle Memorial Institute. The Robotics and Mechanical Systems Group at PNL has been involved in the development and evaluation of robotic systems since the early 1980s. PNL has developed a robotic mannequin for the U. S. Army at Dugway Proving Ground for the testing of chemical warfare protective equipment. PNL has been an integral part of the U. S. Department of Energy's efforts to apply robotic systems to the inspection and clean up of hazardous and contaminated facilities and sites. One of PNL's ongoing projects deals with the application of long reach robotic manipulators to the inspection and waste removal from large underground storage tanks. The inspection of underground storage tanks has many elements in common with the inspection of the internal structures of tankships.

Currently, the inspections of the internal structures of merchant vessel tanks is carried out almost entirely by man-in-the-tank inspections. This requires that the tanks be made safe for manned entry and that the surfaces be cleaned adequately for a visual inspection. The volumes to be inspected inside any one tank are immense. Only a limited amount of the total tank surface area can be inspected by walking the bottom. Safety considerations limit climbing of the side walls to only the lower part of the tank. Scaffolding can be used, or the tanks can be progressively filled with water and rafting used, to examine the tank inner surfaces. These options are time consuming and hazardous. If robotic inspection systems could be applied to the inspection of tankships, the potential benefits are threefold. First, a more thorough examination might be possible if the robotic inspection system could more easily access all of the surfaces inside the tanks. Secondly, less preparation of the tanks would be necessary if manned entry into the tanks were not required. While the surfaces would still need to be cleaned adequately for the inspection, the atmosphere inside the tank would not have to be capable of supporting life. Thirdly, the safety of the operator could be significantly improved by reducing the requirements for accessing confined spaces and climbing to dangerous locations.

The purpose of the "Survey of Robotic Tankship Inspection Technology" was to define general performance requirements for the robotic inspection of tankship internal structures, determine what existing robotic systems were capable of such inspections and develop a computer simulation of the most promising robotic system identified in the industry survey. The intent was to determine what existing robotic inspection technology and systems could be applied to tankships and define what benefits robotic inspections had to offer to the ship inspection community. The work was broken into three tasks.

The first task was to develop general performance requirements for remote robotic inspection of merchant vessel tankships. This task

included reviewing drawings of representative tankships to determine the range of tank internal dimensions to establish realistic reach requirements for robotic systems, based on locations of existing deck access holes. Also included were the determination of the types of defects that a robotic inspection system would be required to detect and characterize. Requirements for portability and operation in the unique environments found on tankships and inside crude carrying tanks were also included.

The second task was to conduct an industry survey of remote inspection technology. This survey included systems for cleaning up hazardous waste sites, inspecting underground storage tanks, inspecting nuclear reactors and other high radiation areas, and discussions with various tankship inspection societies and tankship operators.

The third task was to develop a three-dimensional computer simulation of the most promising robotic inspection system in operation inside a typical crude carrier tank. The computer model of the internal tank structure was anticipated to provide a useful design tool for the demonstration of the operation of current and future systems.

Section 2 of this report discusses the results of the Performance Requirements Definition task. Section 3 describes the results of the Industry Survey task and Section 4 describes the efforts on the Computer Simulation task. Section 5 is a discussion of an assessment of the current robotic inspection systems relative to tankship inspections and a discussion of concepts for future systems. Section 6 contains the Conclusions.

2.0 PERFORMANCE REQUIREMENTS FOR ROBOTIC INSPECTION SYSTEMS FOR TANKSHIPS

This section describes the general performance requirements that a robotic inspection system would need to meet. The general performance requirements were developed so that various robotic systems could be evaluated relative to their ability to inspect tankship internal structures. The intent was to define the defects and damage that needs to be detected and characterized, establish the size and geometry of the tank internal volumes including possible access points, determine the unique safety and functionality issues related to operation on a tankship and inside a crude carrying tank, and to provide a description of the requirements relative to ease of use and the operator interface. The intent was not to develop a performance requirement adequate for procuring a robotic inspection system for tankship inspections. Rather, the intent was to determine what features are necessary for this unique inspection task and to be able to determine if a specific robotic inspection system were capable of accomplishing the task. Development of a procurement specification for the tankship inspection system was beyond the scope of this work.

General performance requirements were developed by reviewing typical drawings of tankships, touring representative tankships during a visit to the USCG Marine Safety Office in Portland, Oregon, contacts with shipping companies and classification societies, and review of available literature.

These initial general performance requirements dealt with the following areas: 1) accessing the interior space and surfaces of the tankship tanks for general visual condition, 2) performing a close-up visual inspection for detailed evaluation, 3) performing ultrasonic thickness measurements, and 4) general functional requirements related to safety and equipment functionality. These general performance requirements were initially developed so that each identified inspection system could be rated relative to its acceptability to the task of remote, robotic inspections of tankships.

No robotic inspection systems were identified which met more than a small subset of the desired performance requirements. Therefore, these requirements have been reformulated to address development needs. The approach was to provide guidance for the design or adaptation of remote inspection systems for tankship use. Due to the diverse types of deployment systems that could be used to position inspection devices (i.e., video cameras and ultrasonic sensors), the performance requirements related to tank access and geometries are expressed in terms of the spaces and surfaces to be inspected. Similarly, performance requirements are presented describing the characteristic of the defects to be detected rather than specific requirements, such as visual acuity. The intent in this formulation of performance requirements is to define the problem to be solved rather than delineate specific characteristics or criteria relative to a specific deployment system.

2.1 REGULATORY AND OWNER-REQUESTED INSPECTIONS

Surveys of tankship are of two types, namely those required by regulatory bodies and those requested by the owners for structural assessment purposes. While concerned with ensuring compliance with regulatory requirements, the owner also requires information on structural conditions that might affect both present and future operating and repair costs of the vessel. The purpose of carrying out any structural survey of a tankship tank is to determine the extent of corrosion wastage and structural defects present in the tank. During a typical internal tank inspection, only a fraction of the internal structural members are inspected. The inspections are focused on critical structural areas. Critical structural areas are those subject to high stresses or with a history of problems.

Class and statutory surveys include annual and intermediate surveys, bottom/docking surveys, special or periodical surveys and occasional surveys. owners' surveys are based on a requirement to assess general condition, corrosion rate, detailed conditions, or for repair assessment.

2.1.1 Class and Statutory Requirements

As far as tank structural assessment for Class is concerned, the special (periodical) survey is of prime importance. The scope of internal structural inspections, as required by the Classification Societies for the special survey, is listed in Table 2.1. The normal interval between each special survey is four years. An overall survey is a survey intended to report on the overall condition of the tank structure and determine the extent of additional close-up surveys. A close-up survey is a survey where the details of structural components are within the inspection range of the Surveyor (i.e., normally within reach of hand). A transverse section includes all longitudinal members such as plating, longitudinals and girders in deck, side, bottom, inner bottom and longitudinal bulkheads.

2.1.2 Owner's Requirements

The type of inspection survey performed depends on the information required to meet the owner's objectives. The surveys may be grouped into four types, although it is not uncommon for these to overlap in practice. These types are general condition surveys, detailed condition surveys, corrosion rate surveys, and repair specification surveys.

General condition surveys are overall surveys of limited scope and time intended to identify gross structural or corrosion-related problems. They involve little or no close-up inspection or thickness determination of internal structures, but give an overall visual impression of the structural integrity and corrosion condition of the tanks inspected.

Detailed condition surveys involve comprehensive close-up visual inspection, and thickness determination of sufficient structural elements in a tank, group of tanks or the entire vessel to accurately assess the present condition. This information is used to determine present and future repairs.

TABLE 2.1. Scope of Structural Survey Requirements

Age < 5 Special Survey No. 1	5 < Age < 10 Special Survey No. 2	10 < Age < 15 Special Survey No. 3	15 < Age < 20 Special Survey No. 4
1. Overall Survey of all tanks and spaces 2. Close-up Survey: a) One complete transverse web frame ring including adjacent structural members (in one ballast tank if any, or a cargo tank used primarily for water ballast) b) One deck transverse including adjacent deck structural members in one cargo wing tank c) Lower part of the girder system including adjacent structural members on one transverse bulkhead in one ballast tank, one cargo wing tank and one cargo center tank	1. Overall Survey of all tanks and spaces 2. Close-up Survey: a) One complete transverse web frame ring including adjacent structural members in one wing tank (in one ballast tank, if any, or a cargo tank used primarily for water ballast) b) One deck transverse including adjacent deck structural members in each of the remaining ballast tanks, if any c) One deck transverse including adjacent deck structure in one cargo wing tank and two cargo center tanks d) The complete girder system including adjacent structural members on the transverse bulkheads in one wing tank (in one ballast tank, if any, or a cargo tank used primarily for water ballast) e) Lower part of the girder system including adjacent structural members on one transverse bulkhead in each of the remaining ballast tanks, one cargo wing tank and two cargo center tanks	1. Overall Survey of all tanks and spaces 2. Close-up Survey: a) All complete transverse web frame rings including adjacent structural members in all ballast tanks an in one cargo wing tank b) One complete transverse web frame ring including adjacent structural members in each remaining cargo wing tanks and one bottom and one deck transverse in each cargo center tank c) One complete girder system including adjacent structural members on the transverse bulkheads in all cargo and ballast tanks	1. Overall Survey of all tanks and spaces 2. Close-up Survey as for Special Survey No. 3 with additional transverses as deemed necessary by the Surveyor

Source: Guidance Manual for the Inspection and Condition Assessment of Tanker Structures [1]

Corrosion rate surveys are limited to several selected areas. Representative thickness measurements of a number of structural components in various tank environments at regular intervals are obtained so that general corrosion rates can be determined for the vessel. In addition, these measurements may identify local corrosion and/or structural problems for the more limited areas surveyed.

Repair specification surveys are of sufficient detail to specify precise steel renewal requirements, structural repairs and reinforcements, corrosion control measures, etc., for inclusion in a

shipyard repair specification. This is the most detailed type of survey, often relying on one of the three other types of surveys, particularly the detailed condition survey to highlight areas of tanks requiring more detailed inspections.

2.1.3 Current Inspection Methods

The current inspection methods are man-in-the-tank inspections. Prior to entry into the tanks, the tanks are cleaned. Tanks and other spaces to be inspected must be sufficiently clean and free from water, scale, dirt, wax and oil residues to reveal excessive corrosion, significant deformation, fractures, and other structural deterioration. Tank cleaning can be performed with the existing crude oil washing system. Continuous forced ventilation should be supplied to the tank during the inspection. All cargo pipelines leading to the tank should be checked for oil content and valves secured closed, immobilized and signs posted. Any oil present in the lines should be removed. All adjacent tanks should be in the same gas free condition as specified for the tank being inspected or be fully ballasted (filled with water). Before beginning any survey, the survey team should ensure that a safety meeting is held to discuss all aspects of safety with special attention being paid to gas testing procedures, command and communication links, and rescue arrangements. An entry permit must be issued by a responsible officer who has ascertained immediately before entry that the tank atmosphere is, in all respects, safe for entry. Before issuing an entry permit, the responsible officer should ensure that the appropriate atmosphere checks have been made for hydrocarbon gases, benzene, hydrogen sulphide and oxygen level. Effective ventilation must be maintained continuously while men are in the tank. Lifelines, harnesses, approved breathing apparatus, resuscitation equipment and other safety equipment must be readily available at the entrance to the tank. A responsible member of the crew is to be in constant attendance outside the tank, in the immediate vicinity of the entrance, and in immediate contact with the responsible officer.

The inspector's tools are generally limited to a flashlight, a pen and pad, a chipping hammer and a scraper to remove rust, scale and oily residue. Safety items include coveralls, hard hat, steel tip shoes, gloves, and possibly a half-mask filter respirator if benzene levels dictate. Additional safety gear the inspector may wish to carry includes safety glasses, pocket oxygen analyzer, and an emergency escape breathing apparatus. The amount of equipment the inspector can carry is limited due to the confined spaces through which he must pass. Other equipment the inspector may wish to carry includes a wire brush, a putty knife and a camera.

The biggest difficulty with performing an inspection of the tank internals is for the inspector to be physically close to the structural members being inspected. The general condition survey is a scanning or screening inspection and is done by visual inspection from accessible locations within the tank. This includes walking the tank bottom and limited climbing to no more than three meters above the bottom or any large stringer platform. Climbing with the use of fall safety devices allows the inspector to inspect the side walls with a proven level of safety. Due to the physically demanding nature of climbing with safety devices, use of fall safety devices is being

recommended for inspecting specific problem areas. Inspection of an area more than three meters from the bottom may also be accomplished with some form of scaffolding or by partially filling the tank with water and rafting. Inspection of under deck longitudinals is sometimes accomplished by hanging from harnesses supported from the longitudinals.

2.2 CHARACTERISTIC OF TANKS TO BE INSPECTED

2.2.1 Tanks to be Inspected

The Very Large Crude Carriers (VLCC) and Ultra Large Crude Carriers (ULCC) are the largest moving objects made by man. An indication of the typical area that must be inspected on such a vessel is detailed in Table 2.2 The task of conducting periodic inspections of such vessels has become increasingly difficult. The large size of vessels has lead to difficulty in accessing the internal structural members, an increase in the time the vessel is removed from service, and an increase in inspection costs.

A typical VLCC, the C. W. Kitto, is shown in Figure 2.1. This vessel is over 1110 ft. long. The cross hatched area in Figure 2.1 is the location of one of the tanks. At this axial location, there are three tanks across the width of the vessel, a center tank and a wing tank on either side. Shown in Figure 2.2 is the cross section of one of the wing tanks. This particular tank is 206 ft. long. Figure 2.3 shows some of the typical structural members inside a tank.

2.2.2 Access Requirements

One of the most severe constraints on remote inspection of the tanks is the very limited access availability. All access to the tanks for inspections is through hatches on the deck. All tanks have one or more oil tight or large bolted hatches and a series of Butterworth hatches. It may also be possible to add special hatches or access ports into the decking, specifically for remote inspection devices.

One, or at most two, oil tight hatches are normally present for manned entry into the tanks. Some tanks also have large bolted hatches. The size of these hatches vary from tank to tank and from vessel to vessel. Representative sizes range from 24-in. x 16 in. elliptical hatches to 48-in. circular hatches.

Tanks also have Butterworth hatches which are used to clean the insides of the tanks. The Butterworth hatches are typically 19-in. circular hatches and are spaced 15 to 20 ft. on center roughly along the centerline of each tank. One Butterworth hatch is associated with each bay of the tank. Each tank is broken into bays by transverse web frames. While there are large openings through the transverse web frames, visual inspections from inside each bay are required to see both sides of all structural members.

TABLE 2.2. Typical Tankship Inspection Areas and Volumes

Vertical Height to Climb for Survey	10,700 M / 35,000 Ft.
Tank Section Area to Inspect	300,000 M^2 / 72 Acres
Total Length of Welding	1,200 KM / 750 Miles
Total Hand Welding (included in above)	390 KM / 240 Miles
Total Length of Longitudinal Stiffeners	58 KM / 36 Miles
Flat Bottom Area	10,700 M^2 / 2.6 Acres
1.0 Percent Pitting	85,000 Pits (each 0.40 mm diameter)

Source: Large Oil Tanker Structural Survey Experience

While it would require modifications to the vessel, it is possible to add additional hatches or ports to the tanks through the deck. Rather small (0.875-in. diameter) holes have been drilled through the deck to permit the video inspection of the upper part of tanks. The addition of new hatches or ports must consider the structural, operational and safety aspects of vessel operation.

2.2.3 Internal Volume to be Inspected

On a typical Very Large Crude Carrier, there are approximately 72 acres of tank section area to be inspected, 750 miles of welds, and 36 miles of longitudinal stiffeners. The largest tank identified from available drawings is 206-ft. long, 90-ft. deep and 55-ft. wide. This tank is on a Very Large Crude Carrier. The largest tank identified from available drawings of an Ultra Large Crude Carrier is 129-ft. long, 99-ft. deep and 46-ft. wide. The tanks are roughly rectangular in cross section. The top to the tank is the deck of the vessel. The bottom of the tank is generally the bottom skin of the vessel except for double-hull designs where the bottom of the tank is a plate between the tank and a ballast tank. The sides of the tanks are either the external skin of the vessel or bulkhead between tanks. The ends of the tanks are oil tight bulkheads. The corners of the tanks are usually square except for the outside wall of a wing tank. The outside corners on wing tanks are generally radiused.

Each tank is broken into several bays by transverse web frames. These frames are typically spaced 15 to 20 ft. apart.

2.2.4 Geometries of Structural Members to be Inspected

The vessel and its tanks obtain their strength from a series of internal structural members. Figure 2.2 shows a cross section through a typical tanker. The deck plating is stiffened by a series of

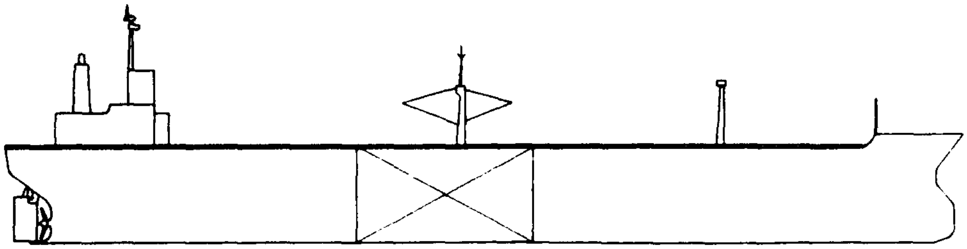

FIGURE 2.1. A Typical VLCC, the C. W. Kitto

longitudinal girders and other smaller longitudinals. The tank bottom plating is also stiffened with longitudinal girders and bottom longitudinals. The tank side shells are stiffened with longitudinals. Transverse stiffness is obtained in the wing tanks with transverse web frames. These frames have various stiffeners in the horizontal and vertical directions. Center tanks usually do not have a complete transverse web frame, but rather a bottom transverse and a deck transverse.

At the ends of most tanks are vertical stiffeners and horizontal plates known as stringers. These stringers can, in some cases, limit the amount of the transverse bulkhead that is directly visible from the Butterworth hatches.

Many of the reinforcing members have cutouts which allow the passage of crude from one bay to the next. Many members also have cutouts to accommodate other structural members and to reduce stress concentrations.

There are numerous other plates and flat bars used to strengthen and reinforce the connection between the various other structural members in the tanks.

Normally, the side walls on the center tanks do not have significant structural members attached. The stiffness of these bulkheads is provided by the structural members attached on the wing tank side.

Depth or width of structural members typically ranges from 1 to 4 ft. Spacing between structural members is typically 2 to 4 ft. Most girders have a "T-shaped" cross section, and many longitudinal and transverse stiffeners have an "L-shaped" cross section.

Additional plates may have been added to structural members to repair previous damage.

Welds, especially welds at the intersections of multiple members, are primary candidates for fracture. Remote inspection systems must be able to visually inspect welds on both sides of essentially all members.

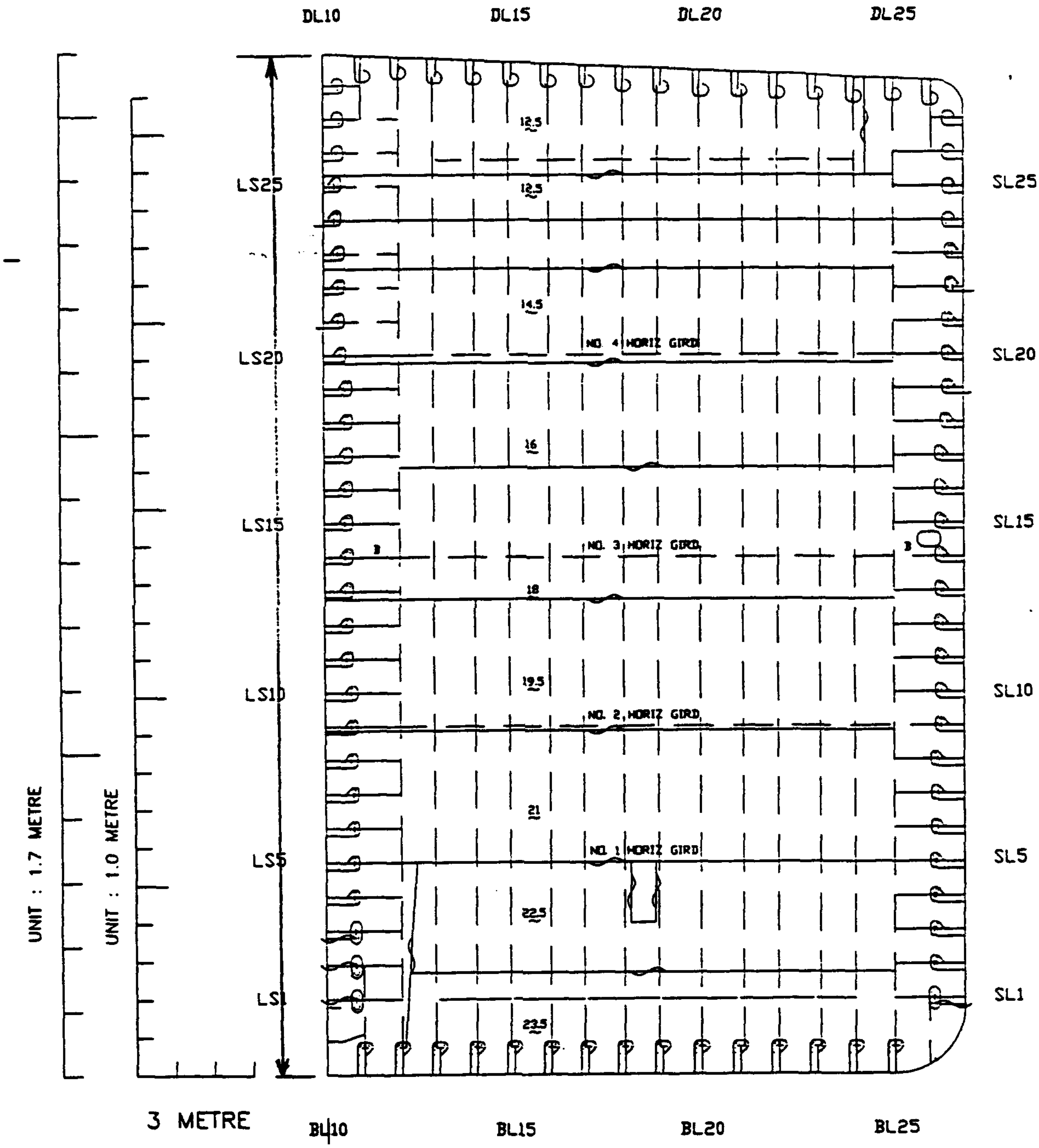

FIGURE 2.2. Cross Section Through Wing Tank

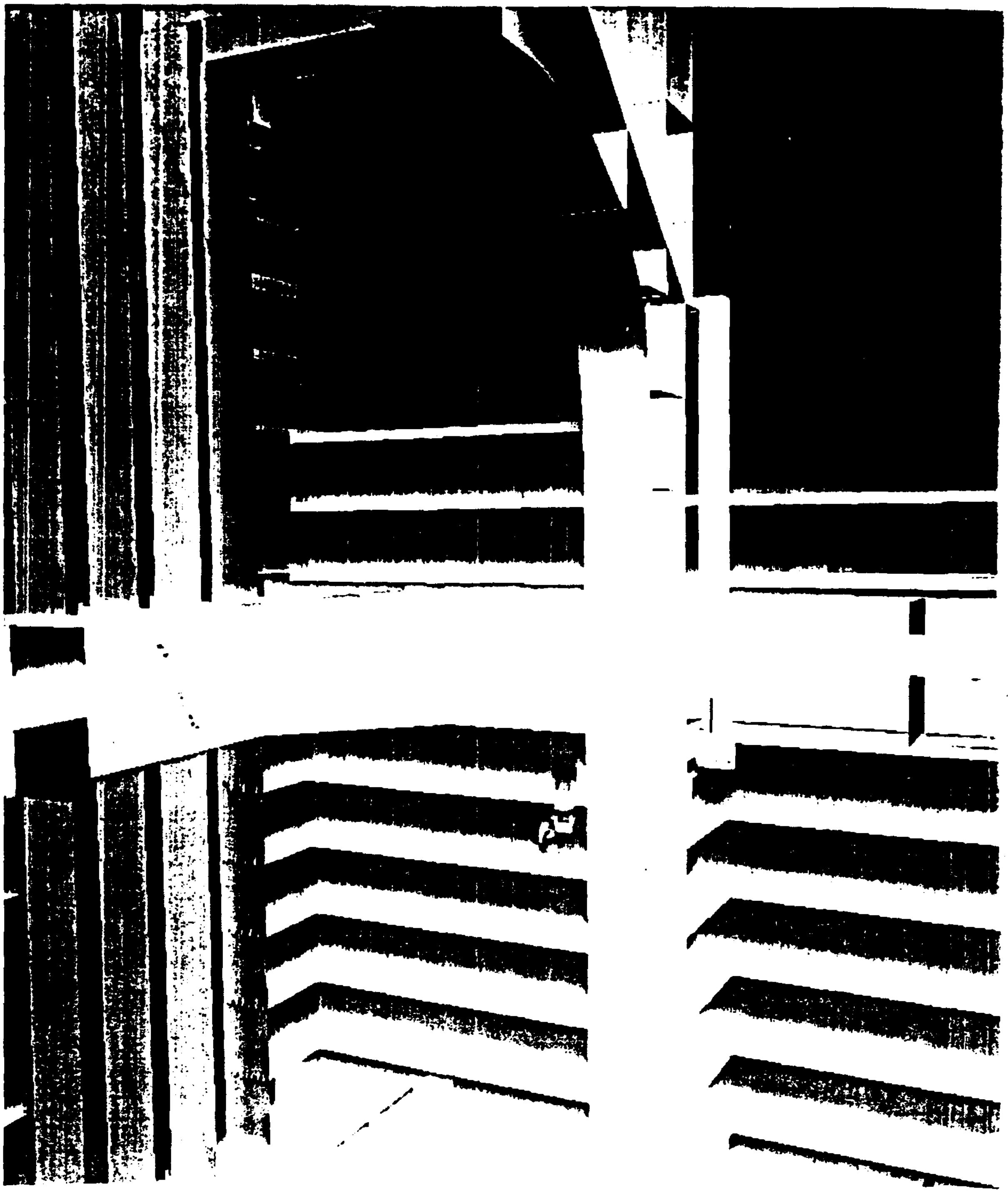

FIGURE 2.3. Typical Tank Structural Members

2.3 CHARACTERISTICS OF STRUCTURAL DEFECTS

2.3.1 Types of Defects/Damage

Structural defects include weld defects, buckling, and fractures. Fractures initiating at latent defects in welds commonly appear at the beginning or end of a run, rounding corners at the end of a stiffener, or at a weld intersection. Fractures may also be initiated at stress concentrations. Intermittent welding may cause problems because of the introduction of stress concentrations. Corrosion of welds may be rapid because of the influence of the deposited metal. The extent of the heat affected zone may also influence the weld quality. Figures 2.4, 2.5, and 2.6 show typical locations for fractures in tank welds.

Fractures may not be readily visible due to lack of cleanliness, difficulty of access, poor lighting, or compression of the fracture surfaces. It is therefore important to identify and closely inspect potential problem areas. Fractures will normally initiate at notches, stress concentrations or weld defects. If these initiation points are not readily visible, the structure on the other side of the plating should be examined.

The following areas, where structural defects might occur, should be given special attention during the survey:

1) ends of principal girders, stringers, transverses and struts with associated brackets; particular attention should be paid to toes of brackets,

2) bracketed ends of shell, deck and bulkhead stiffeners,

3) connection of shell, deck and bulkhead longitudinals to transverse web frames; particular attention should be paid to the side shell connections between full-load and ballast waterlines,

4) any discontinuities in the form of misalignment or abrupt change of section,

5) plating that covers cut-outs and openings, and

6) areas which show any evidence of damage or buckling.

Permanent buckling may arise as a result of overloading, overall reduction in thickness due to corrosion, or damage. Elastic buckling will not be directly obvious, but may be detected by coating damage, stress lines or shedding of scale.

Several types of corrosion may be present. These can be categorized as pitting corrosion, general corrosion, grooving corrosion and weld metal corrosion.

Pitting corrosion is a localized corrosion that occurs on the bottom plating and other horizontal surfaces that trap water. For

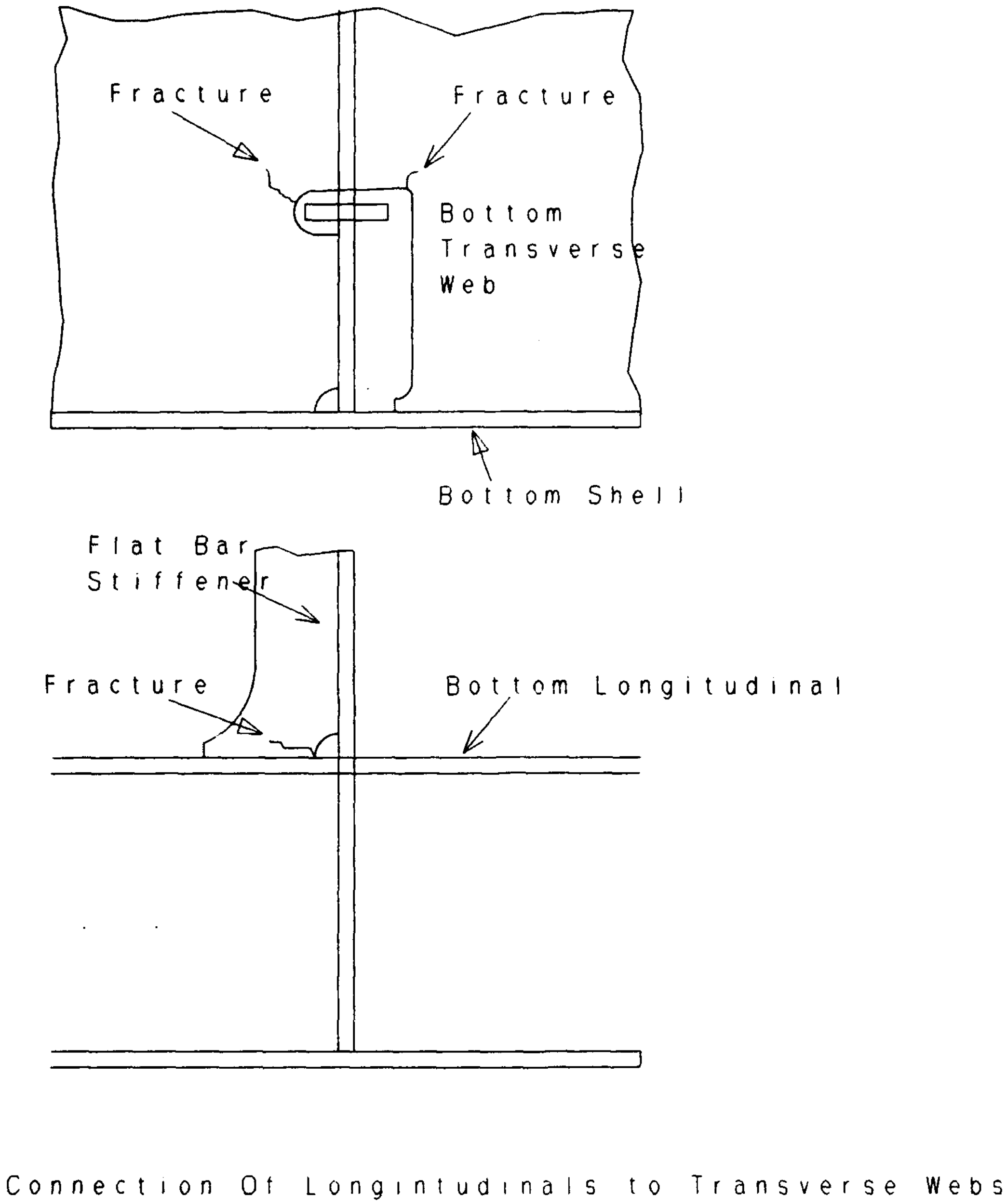

FIGURE 2.4. **Typical Fracture Zones - Longitudinals**

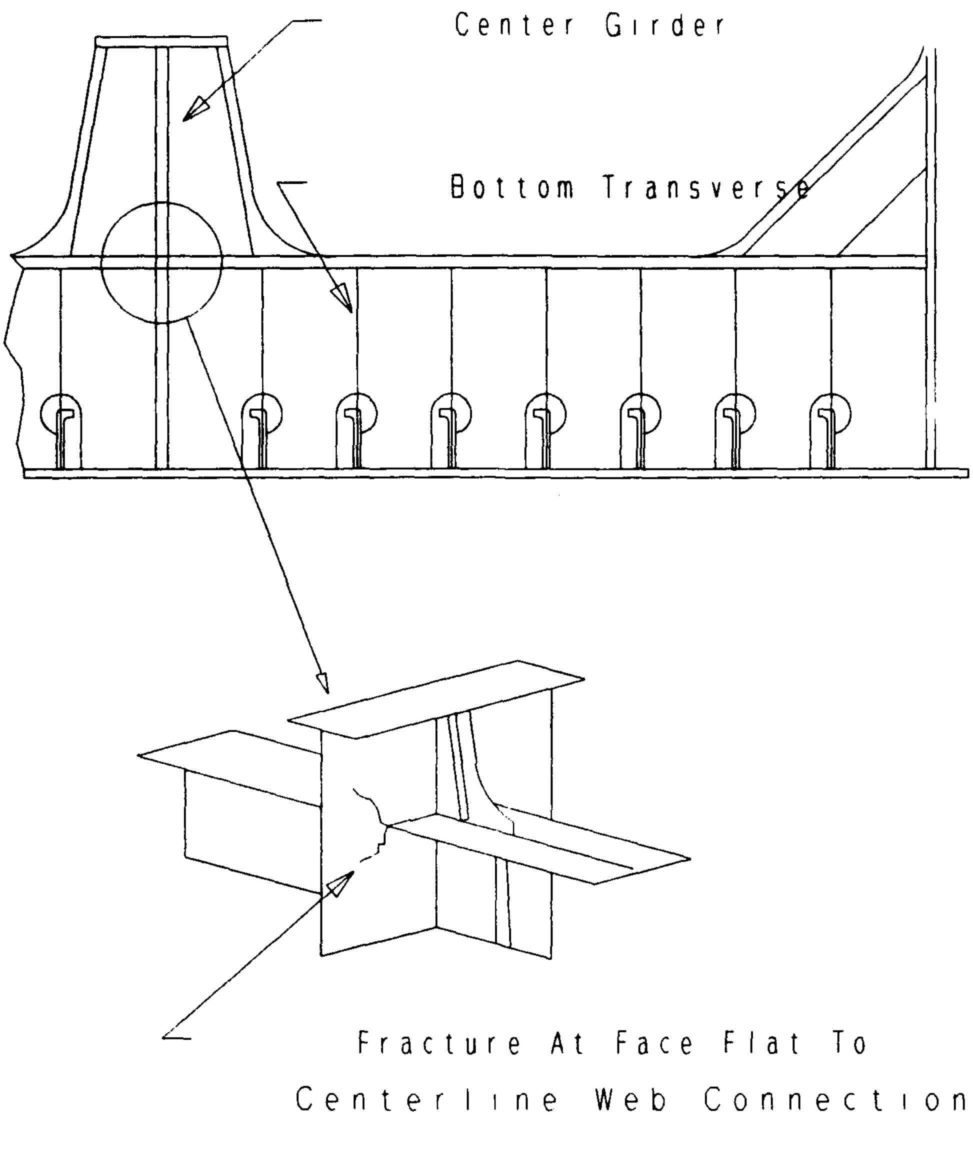

FIGURE 2.5. Typical Fracture Zones - Centerline Web

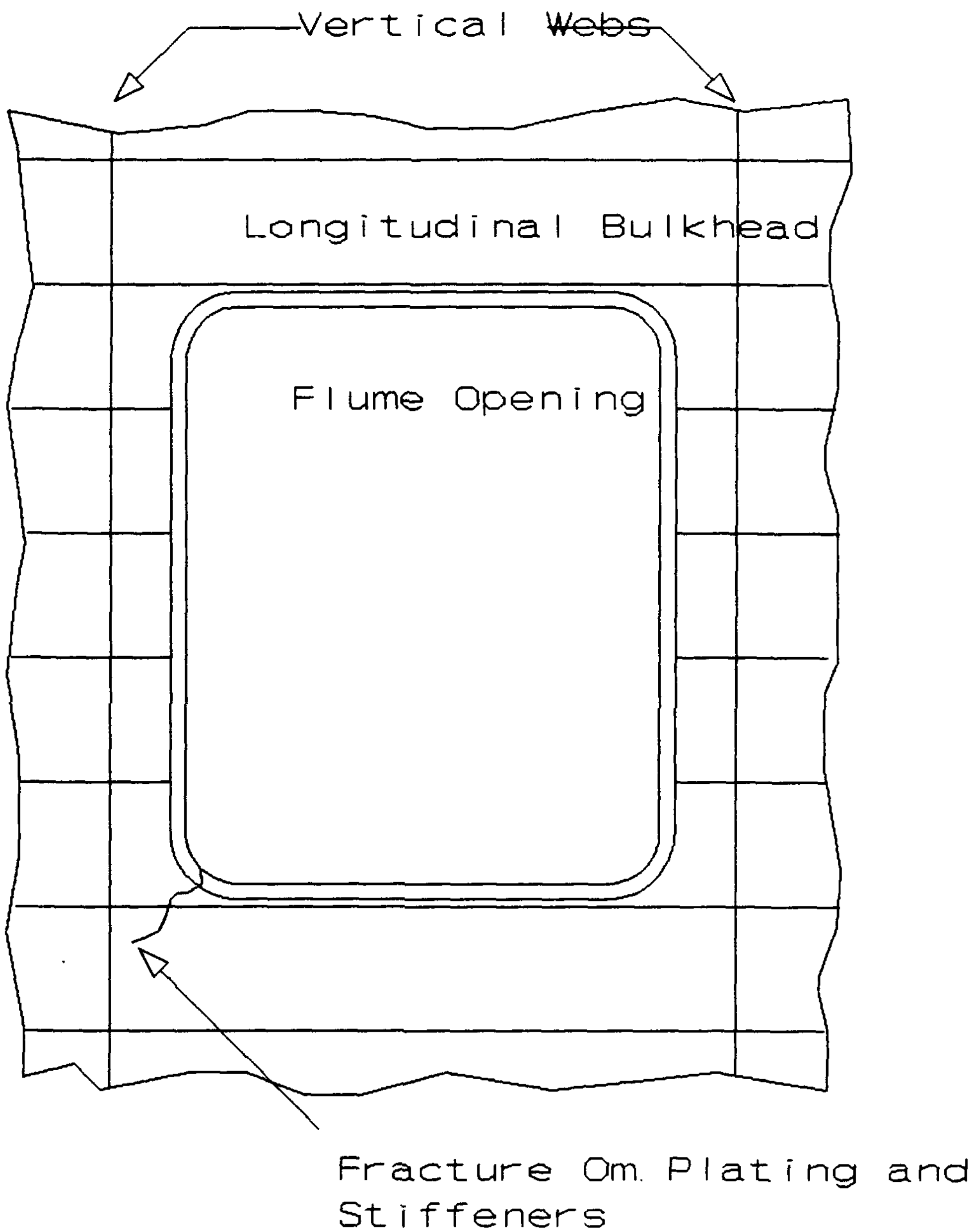

FIGURE 2.6. Typical Fracture Zones - Bulkhead

coated surfaces, the attack produces deep and relatively small diameter pits that can lead to hull penetrations in isolated random places in the tank. Pitting of uncoated tanks, as it progresses, forms shallow but very wide scabby patches. The appearance resembles a condition of general corrosion. Severe pitting of uncoated tanks can affect the strength of the structure.

General corrosion appears as a non-protective, friable rust which can uniformly occur on tank internal surfaces that are uncoated. The rust scale continually breaks off, exposing fresh metal to corrosive attack. Thickness can not usually be judged visually until excessive loss has occurred. Severe general corrosion in tankers, usually characterized by heavy scale accumulation, can lead to extensive steel renewals.

Grooving corrosion is a localized, linear corrosion which occurs at structural intersections where water collects or flows. This corrosion is sometimes referred to as "in-line pitting attack", and can also occur on vertical members and flush sides of bulkheads subject to flexing.

Weld metal corrosion is defined as preferential corrosion of the weld deposit.

2.3.2 Ultrasonic Wall Thickness Measurement

Ultrasonic thickness measurements are an essential part of most tankship surveys and are used to determine the residual thickness of structures in critical areas. A remote ultrasonic measurement system would require a video system to monitor positioning of the NDT equipment.

The remote NDT system places the ultrasonic probe and its related hardware near the surface to be measured. Some method must be available to clean the scale, rust, dirt, and perhaps paint, from the surface to be measured. The face of the ultrasonic probe must then be positioned parallel to the steel surface. This can be difficult even for a human operator on a corroded surface. If a conventional contact ultrasonic transducer is used, either water or oil is required for acoustic coupling. Depending on the use of the ultrasonic data and the inherent inaccuracies in the system, several measurements may be required in a specific area. Another ultrasonic method that does not require a couplant uses electromagnetic acoustic transducers (EMAT).

The performance specifications for the NDT wall thickness measurements will contain several categories similar to the visual inspection systems. In addition, there will be specific requirements related to accuracy of the wall thickness measurements and to the meeting of recognized industrial standards, such as ASTM E317, for the overall system. Ultrasonic inspection systems present their own special safety consideration since they are not usually constructed to be intrinsically safe.

2.3.3 Conditions of Surfaces to be Inspected

The tanks to be inspected must be sufficiently clean and free from water, scale, dirt and oil residues to reveal excessive

corrosion, significant deformation, fractures, and other structural deterioration. It is assumed that for a remote visual inspection, the surfaces of the tanks will have to be cleaned to a condition similar to that currently required for a man-in-the-tank inspection. Tank cleaning will likely be performed with an existing crude oil washing system. Cleanliness of the tank prior to inspection is essential for remote inspections. While the inspector can currently use a wire brush or scrapper to remove wax, sludge, mud or corrosion, the operator of a remote inspection system will not be able to do local cleaning to expose potentially damaged or degraded areas, unless special features are added to an inspection system. In terms of an overall inspection system, one that could do localized cleaning has the potential to be more efficient and cost effective.

The surfaces to be inspected are primarily carbon steel, corroded carbon steel and coated steel. The surfaces are generally dark and do not reflect a large amount of light.

Three types of internal tank inspections are considered. The first is the general condition visual inspection. The second is the close visual inspection to detect small cracks and welding defects. The third is ultrasonic thickness measurements.

A video-based system is the primary method envisioned for both general condition visual inspections and close visual inspections. Both single camera and binocular video systems are applicable to the inspection of tankship internals. Ease of use, expense and usefulness of the obtained images are trade-offs to be considered. Black and white versus color cameras are another variation. Here, the trade-offs are the amount of light required versus the ability to detect color-related clues such as rust. While one normally thinks in terms of moving video, still video has the potential advantages of lower light requirement and greater resolution. Each inspection system should be evaluated on its ability to detect and characterize the various defects described in this section.

It is very difficult to quantify the size and other characteristics of defects that must be detected by a remote inspection system. While it is reasonable to set a minimum detectable crack length of 1 in., it is very challenging to set limits on the widths of fractures that must be detected. It is also hard to quantify the level of various types of corrosion that must be detected. None of the reviewed literature discussed the specifics of defect characterization in quantifiable terms. Therefore, the most reasonable approach is to specify the required visual acuity of the inspection system. The basis for specifying the visual acuity requirements is that the complete system which includes the deployment device, lighting, video camera, monitor and operator must be capable of detecting buckling, fractures and corrosion defects with a reliability similar to the current man-in-the-tank method. For general condition inspections, the system must be able to detect defects which are visible to the unaided human eye with 20/20 vision from a distance of 10 ft. using a large hand held light. For close-up visual inspections, the system must be able to detect defects visible to the unaided human eye with 20/20 vision from a distance of 2 ft., again using a large hand held light.

2.3.4 Lighting Requirements

The available light inside the tanks is minimal. A limited amount of light enters through the hatches but does not generally illuminate a very significant part of the tank. Any video-based inspection system will have to include the lighting required by the video camera. Required lighting will depend on the sensitivity of the camera, the distance from the camera to the surface, and the focal length of the lens. Additional requirements associated with the lighting are related to the safety concerns described in Section 2.4.2. Depending on the atmosphere inside the tank during inspection, the lighting may have to be explosion-proof.

2.4 OPERATIONAL CHARACTERISTICS

2.4.1 Ease of Use

One of the requirements for ease of use that was specifically included in the Statement of Work for this project is that the system must be man-portable. The system must be small enough to be brought on board ship, assembled and operated with a limited amount of man power. The definition of man-portable used here is a system that: 1) requires no more than three persons to transport and assemble, 2) is transportable in suitcase-sized containers, and 3) can be operated by one person.

During operation, the system must be easy to use. All systems that have been envisioned utilize some type of video camera with the visual interface to the operator being a television monitor. In order for the system to be useful, the operator must be able to view the monitor for extended periods without suffering eye strain. The video image must also be stable. This means that the video camera should not oscillate to an extent that the video image on the monitor is degraded. The amount of camera motion that can be tolerated is related to the focal length of the camera lens and the proximity of the camera to the surface being viewed. The use of still video cameras may provide a better operator interface by eliminating image oscillations. Fuzzy logic controllers have been developed to improve video image oscillation problems.

Ease of use of the robotic controls will be mandatory. The interface between the operator and the inspection system should be as instinctive as possible. While a fully robotic inspection system, or at least a system that will perform some of its task in a fully robotic mode, may ultimately be developed, the initial robotic inspection systems will undoubtedly be telerobotic. Under telerobotic control, the operator will be controlling the motion of the robot by direct input to a control device such as a joy stick. Feedback will be required so that the operator can easily determire where the robotic inspection system is in the tank and what part of the tank is currently being displayed on the monitor. The images from the inspection will be stored for documentation and possible review at a later time. It is imperative that information be stored with the video images that define what part of which tank on which tankship is being displayed. Also, the operator should be able to make voice annotations on the video tape.

Collision avoidance schemes would be required for the inspection system because the operator would not have visual contact. If the deployment system utilizes a long reach manipulator arm, means must be included to prevent the arm from hitting any of the in-tank structures and damaging the tankship or the inspection system. This might be implemented by using full-arm proximity sensors or by using a computer model of the tank geometry in conjunction with a kinematics model of the arm. An alternate method might be to provide multiple, in-tank cameras to allow the operator to determine the position of the arm. However, the amount of lighting required for such a scheme might be prohibitive. If the deployment system is a remote vehicle, such as a submersible, considerations must be given to prevent tangling of the tether line.

2.4.2 Safety

The potential for fire and/or explosion on board a crude carrier is a primary concern. Design and operation of a robotic inspection system for use inside a tank that has carried petroleum products requires special attention to the hazards of explosion. Robotic systems, even if hydraulically or pneumatically operated, require electrical or electronic sensors to measure parameters such as joint angle positions. Some components of robotic systems can not currently be made intrinsically safe for use in an explosive environment. The lights for the video cameras may be the most difficult components to make safe. The lights will have to either be made explosion-proof or the atmosphere inside the tank made non-explosive. One of the advantages of a submersible inspection robot is that the tank is filled with water, thereby reducing the explosion hazards. It may be possible to use an inert gas purge or otherwise alter the in-tank atmosphere to address the explosion issues.

One aspect of robotic operation that must be considered is the potential for the robotic device to injure a person or damage equipment within its reach envelope. It was discussed above that the robot should have systems to prevent its impacting the inside of the tanks and damaging the tank or itself. The robot must not be able to operate in such a way that it could injure the operator or other persons. One concept for an inspection system would use the robotic system to augment the in-tank inspection carried out by a person. Under this scenario, the robot might be operated while a person was inside the tank, but only if the person was outside the reach of the robot. Sensors could be used to prevent the robot from moving whenever a person entered or approached the system's work envelope.

2.4.3 Functionality

There will be many performance specifications related to whether the inspections are done in dry dock or at sea, what type of deployment system is used, the size and condition of the tanks, and other practical considerations.

In general, there may be no ship's electrical power available at the location where the inspections will be performed. The inspection system will have to possess its own power supply. There is a possibility that the ship's pneumatic or fire water supply could be

used for power, but this has not been investigated. All requirements for safety will have to be applied to the power supply.

The system must be able to be transported, assembled and operated on board the tankships under a wide range of environmental conditions. The equipment must be waterproof and resistant to any chemicals it might come in contact with.

3.0 INDUSTRY SURVEY

A literature search and market survey were performed to identify robotic inspection systems and technologies that were either directly applicable to tankship inspections or had the potential for adaptation to tankship inspections.

The literature search was conducted on the National Technical Information Service (NTIS), which is part of the U. S. Department of Commerce. A keyword list was developed for searching the database. Searches were made for robotic inspection systems for tankships, marine vessels in general and other areas with similar remote inspection requirements, such as nuclear facilities. A subset of the database contained a significant number of article citations from the COMPENDEX Database relative to Nondestructive Testing of Surfaces, Coatings and Paints.

The market survey was conducted by contacting commercial manufacturers, tankship owners and inspection societies to determine what types of robotic inspection systems were currently available or being developed for the remote inspection of tankships. Vendors of robotic inspection systems for the nuclear industry were also contacted to determine if some of their equipment would have application for tankships.

Technical specifications for each system were not collected during the literature search and market survey. The objective of the survey was to determine if a specific system or technology was applicable to tankship inspection. The understanding of the performance requirements was used to categorize each system or technology as either applicable or not applicable to tankship inspection.

The literature search and market survey resulted in few systems that could meet the unique requirements of robotic tankship inspection. No other remote inspection task was identified having similar performance requirements to tankships. The unique combination of huge volumes to be inspected, the long distances to be spanned, the limited available lighting, limited access and the desire for a man-portable system are unique and rigorous. Only systems specifically intended for this application are likely to have the right combination of attributes.

Our literature search and market survey were focused on complete inspection systems. An inspection system was considered complete if it contained both a visual inspection device, such as a video camera, and a deployment system. Of all the systems located during the investigations, only two were found that were specifically designed for tankship inspections, ARTIS and NETSCO. Additional systems were found that were not specifically designed for tankship inspections but had many of the required characteristics. Although none of these latter systems could be used in their current configuration for tankship inspections, they represent technology that could be adapted.

In addition to complete inspection systems, key components, such as video cameras, were looked at separately. Also, robotic devices that could deploy video cameras and ultrasonic probes were evaluated.

Except for the ultrasonic wall thickness measurements, the inspection requirements for tankships are visual. While other "visual" inspection devices may be used eventually, for at least the near future, some version of a video camera will be used for the remote inspection of tankships. Therefore, the market survey also included various camera types and vendors.

The market survey also included robotic devices that could be used to deploy a video system and possibly position ultrasonic probes. The scope of this survey of robotic deployment devices focused on long reach manipulators and did not specifically include submersibles and crawlers/climbers. These latter robot types could have applications to some subset of the overall tankship inspection task. However, they were not considered to have the potential for meeting the overall inspection requirements. While submersibles and crawlers/climbers could be used for close-up inspections, they have limited application to general, overall inspections due to either limited viewing range or slow operational speeds.

3.1 INSPECTION SYSTEMS DESIGNED FOR TANKSHIP INSPECTIONS

Two systems were found that were specifically designed for the task of inspecting tankship tanks. While neither of these systems meet all of the desired performance requirements, they both represent useful application of remote inspection technology to the task at hand. The more sophisticated system was the Advanced Remote Tanker Inspection System (ARTIS). ARTIS is a remotely piloted submersible that performs inspections of the tanks when they are filled with sea water. The other system is an inverted periscope being developed by NETSCO and BP. This device is inserted into the tank through the Butterworth hatches and extends about eleven feet below the deck. It is used for visual inspection of the under deck structures.

3.1.1 ARTIS

From 1984 to 1986, the Honeywell Underseas Systems Division/Hydro Products Operations developed ARTIS for Mobil Oil specifically for the inspection of holds of oil tankers in ballast for corrosion or damage. ARTIS was designed to provide both video inspection and ultrasonic plate thickness measurements. The vehicle was designed to be operated while the tanker is docked or underway.

ARTIS is comprised of the remotely operated vehicle, underwater power unit, and control console. The control console is located in the tanker's deckhouse and is connected to the underwater power unit via the fiberoptic deck cable. The underwater power unit is connected to the vehicle via the umbilical cable. One unique feature of the ARTIS was the approach used to create an intrinsically safe system. The vehicle is operated under water. Power for the unit is generated with an underwater generator which uses water from the fire main to turn a water turbine. All connections to ARTIS which exit the tank

are by fiber optic cables. The system has no energy on deck which could ignite a volatile gas.

ARTIS uses a single color CCD camera with lighting for close-up inspection. The system also has an ultrasonic measurement system for measurement of plate thicknesses. It is claimed to be useable on rough, corroded steel surfaces without grinding before the inspection. Special purpose cleaning tools, which allow preparation of the steel surface for taking ultrasonic thickness measurements, were developed as part of the system.

ARTIS was tested both dockside and at-sea aboard the vessel MOBIL AL HARAMIN, the vessel EXXON BENECIA and the vessel MOBIL ARCTIC. Results of the tests were reported to be promising. The system was generally useful for the inspection of the internals of the tanks. Information relating to how fast the system was able to perform the inspections was not available. Due to the nature in which the inspections are performed and the relatively small field of view, the system requires the vehicle to traverse close to all areas to be inspected. One reported problem with ARTIS, which could be corrected with further development, was the difficulty the operator had with keeping track of where the vehicle was inside the tank. It was difficult to be sure all surfaces had been inspected.

Development of ARTIS was stopped in 1987 and, to the best of our knowledge, there are no current plans to restart the project. Science Applications International Corporation has subsequently acquired all rights to ARTIS.

ARTIS was designed to perform most of the inspection requirements that are discussed in Section 3. The close-up visual inspection requirements appear to be met, although quantitative information was not available on the ability to detect defects. The ability to conduct ultrasonic thickness measurements was an integral part of the system. However, the ability to perform a general visual inspection of structural members was limited by the effective range of the video cameras while operating under water. The system was designed with consideration of the safety aspects of working on a crude carrier. The submersible was small enough to fit through the available access ports, but the system probably does not meet the definition of man-portable.

No cost information was available for the ARTIS system.

3.1.2 NETSCO/BP Inverted Periscope

A remote inspection device is being developed jointly by NETSCO and BP. This device is used for inspection of under deck structures. It has a low light, black and white video camera with zoom capability. The device is a remotely operated device but is not robotic.

This device is portable and can be handled and set up by two people. It accesses the tank through the Butterworth hatches and extends approximately eleven feet into the tank. It has the capability of 360 degrees of rotation about the vertical axis and has pan and tilt capabilities.

Early tests with the device demonstrated its ability to detect fractures. In these tests, it required approximately three days to inspect the underside of the deck through seventy Butterworth hatches. Approximately four set ups were possible per hour. This device is currently used only in port because the tanks must be cleaned to permit the surfaces to be inspected.

3.2 INSPECTION SYSTEMS SOMEWHAT APPLICABLE TO TANKSHIP INSPECTION

Following is a discussion of those systems that were found which had some of the attributes necessary to tankship inspections. While these could be used for some remote inspection tasks, they could not be used without modification to tankship inspections. They are presented as examples of generally relevant remote inspection technology.

3.2.1 SONSUB

While SONSUB does not have a system for the inspection of VLCC and ULCC tanks, they have developed long reach manipulator systems for other inspection tasks. They are currently developing a prototype inspection system for the Federal Highway Administration that will be used for sonar inspections under bridges. This trailer-mounted machine sits on the bridge roadway and uses a telescopic arm to position a sonar probe up to 50 ft. below the bridge, see Figure 3.1. An on-board computer monitors the various length and angle sensors on the system and calculates the position of the sonar probe and depth of the water. The SONSUB system could not be used for tankship inspections; being mounted on a trailer makes it impractical. The system is not intended for visual inspection but could be adapted to this inspection need. While the reach of the arm is less than required for a complete close-up visual inspection of a tank, adaption of the design to longer reaches appears feasible. Access constraints would be a major limiting factor.

SONSUB is also involved in other remote handling and inspection systems. A large percentage of their business comes from offshore operations in the oil field, which includes heavy utilization of vessels. While they have no equipment directly applicable to the problem of tankship inspections, they are confident that the technology is available for them to develop a system for the remote inspection of tankship tank internals based on the use of long reach manipulators operating through the Butterworth hatches. An estimate of $500,000 to $700,000, with a schedule of 6 to 9 months, was offered based on a discussion with SONSUB.

3.2.2 Long Reach Manipulators

The initial focus during the search for robotic deployment systems was on long reach manipulators. Long reach manipulators are being explored as devices to assist in the inspection of underground storage tanks. There are many similarities between the requirements for the inspection of underground storage tanks and tankship tanks. Access to the areas to be inspected is limited in both cases and the large volumes to be inspected are similar. Similar inspection requirements apply to both applications.

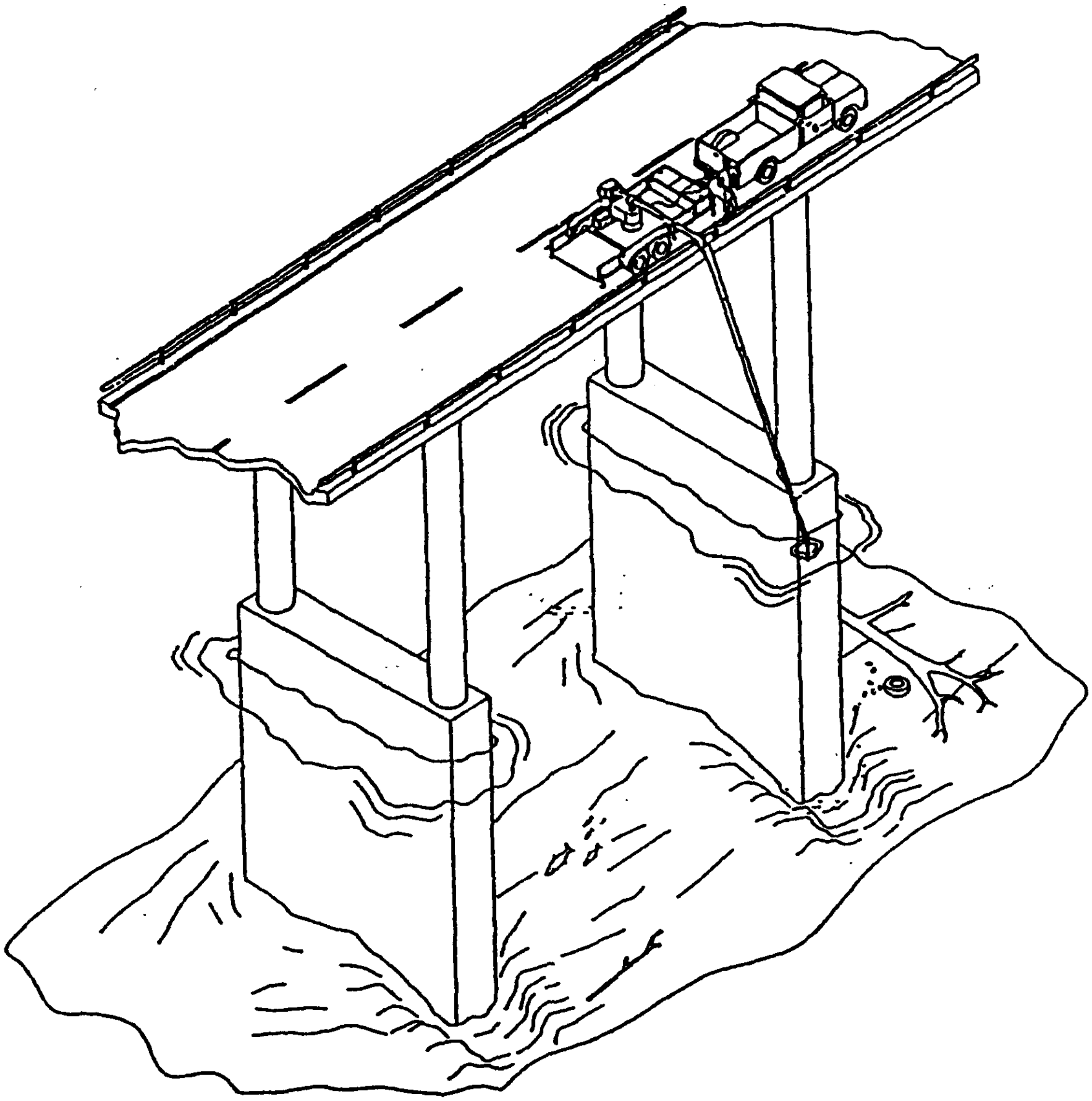

FIGURE 3.1. SONSUB

An extensive survey of commercially available booms (long reach manipulators) was conducted as part of a program at Hanford for the removal of waste from an underground tank. The objective of the work was to determine if there were commercially available booms which could be used in their normal configuration or in a "readily modifiable" configuration in the tank. Access to the tank was through a 42-in. diameter hole approximately 15-ft. long. The horizontal reach requirement was 38 ft. with a vertical reach of 40 ft. The study found no commercially available booms that could be used without modifications. Some potential was seen for adaptation of existing equipment or development by crane manufacturers of useable designs. While no commercially available manipulator has been procured for use in the underground storage tanks, a specially designed manipulator is being procured. However, the weight of the manipulator for underground storage tank use can be much greater than for tankship inspection because of tankship deck loading limits. The weight of the cranes was measured in tons and would obviously not meet the requirement of being man-portable and could not be supported by the ship deck. The size of the available access on the ship deck also eliminates the cranes from consideration.

Special purpose robotic systems also exist for the inspection of various reactor vessels, radiation containing enclosures and hot cells. These devices are specifically designed for rather limited scope inspection tasks and are not applicable to tankship inspections.

Another application of long reach manipulators is in space. However, long reach manipulators developed for space applications are not viable for terrestrial use due to the self-induced loads from gravity.

4.0 COMPUTER SIMULATION OF TANKSHIP INSPECTION ROBOT

A three-dimensional computer model of one bay of a wing tank from a Very Large Crude Carrier and a robotic inspection system was prepared using the IGRIP computer code. IGRIP was developed by Deneb Robotics, Inc. of Auburn Hills, Michigan. The IGRIP software is a computer graphics-based package for work cell simulation and off-line programming of robots, which was originally developed as a tool for laying out work cells for automated robotic assembly of automobiles. The IGRIP software is a product of Deneb Robotics, Inc. of Auburn Hills, Michigan. Objects can be modeled using Computer-Aided Design (CAD) tools. The IGRIP code includes a library of robots and other mechanical systems. Additionally, new robots can be modeled by assembling parts created in the CAD environment into devices with multiple degrees-of-freedom. Robotic devices can be programmed to include geometric and non-geometric information, such as kinematics and dynamics. The motion of the robotic devices can be programmed to execute selected motion sequences while the viewer's position and perspective is being dynamically changed.

The data for the model of the wing tank bay from the Very Large Crude Carrier was obtained from CAD files supplied by the U.S. Coast Guard. Only a single bay of the tank was modeled. This provided an adequate representation of a postulated inspection sequence. Including a larger expanse of the tank would have required that less detail be included in the surfaces represented in the model. It is probable that only a single bay of a tank would be inspected by a robotic inspection system due to the constraints imposed by the limited access points and the extensive amount of internal structures. With the level of detail that was used, a fairly good evaluation can be made of the inspection coverage that can be obtained using the selected robotic inspection concept. The model included all of the major structural components in the tank, including the deck. Figure 4.1 shows the model of the tank bay.

Since no robotic inspection systems were found that were adequate for the inspection of tankships, a robotic concept was developed that had many of the desired attributes. The robotic device was assembled in the IGRIP code using components from two existing robotic devices. The concept consists of a long vertical mast with a single degree-of-freedom with a six degree-of-freedom robotic manipulator mounted on the bottom end. The inspection system would consist of a video camera and light mounted at the end effector of the manipulator. The robotic inspection concept is shown in Figure 4.2. It should be noted that, while the selected concept has realistic kinematic and dynamic properties, the concept may not meet many of the requirements mentioned in Section 2 of this report. Specifically, the concept would not be man-portable and may put unacceptable loads on the deck. While the selected manipulator is hydraulically powered, it contains electrical sensors which are not intrinsically safe.

Once the models of the tank bay and the robotic inspection concept were completed, a representative inspection sequence was developed. The motion of the device can be watched on one half of the computer monitor while the view from the simulated camera mounted on the end effector is shown on the other half of the monitor. The

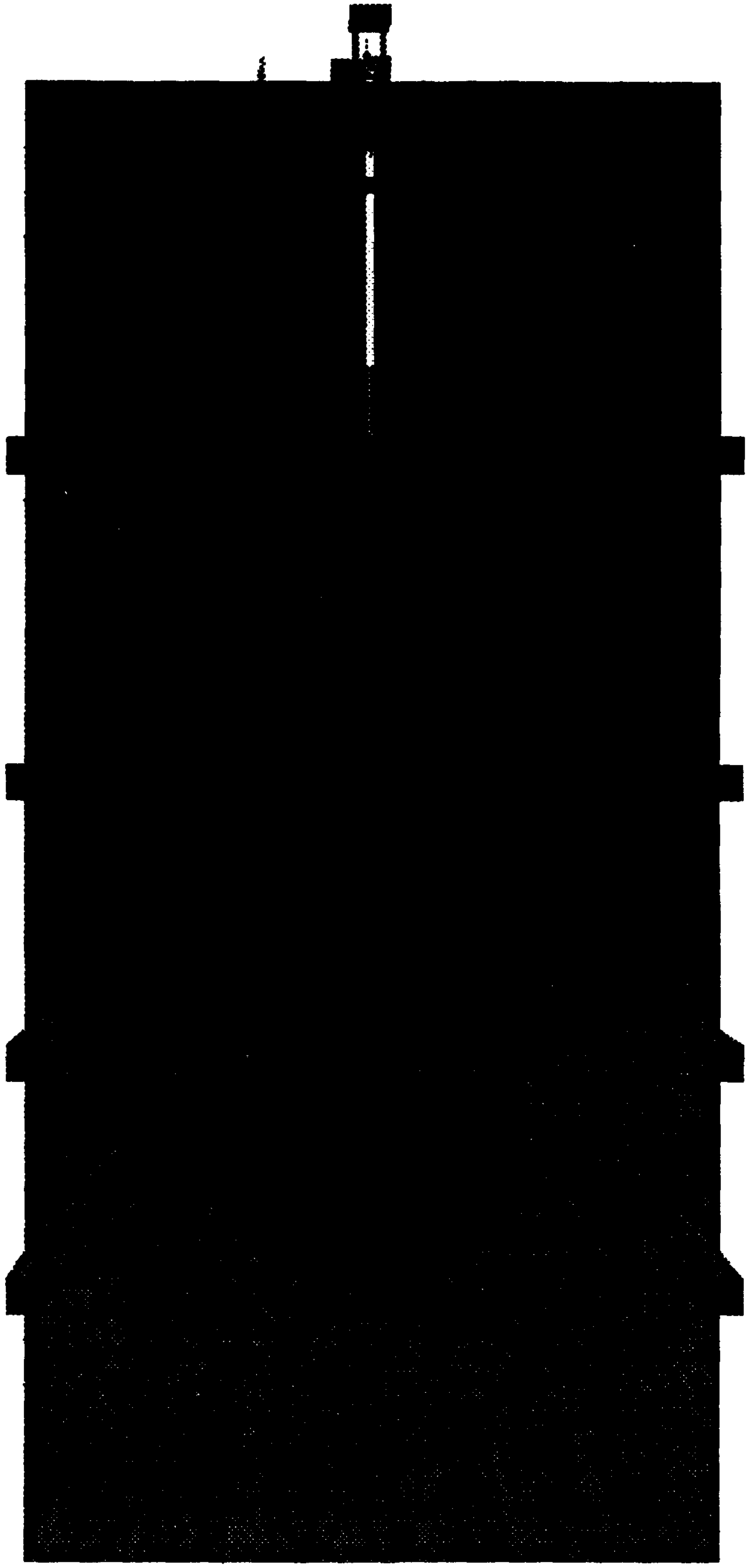

FIGURE 4.1. IGRIP Model of Tank Bay

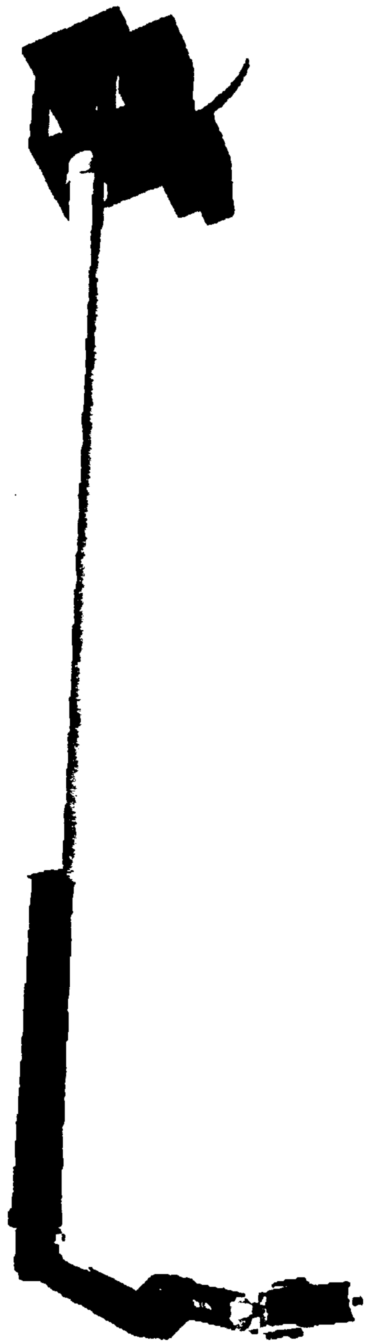

FIGURE 4.2. Robotic Inspection Concept

simulation has the ability to vary the available lighting and the effective focal length of the simulated inspection camera. By carefully watching the simulation, a good estimation can be made of the potential usefulness of selected inspection scenarios. The use of such computer simulations could be a very useful part in the design of robotic inspection systems specifically developed for tankship inspections.

A video tape showing the computer simulation is provided with this report.

5.0 ASSESSMENT OF CURRENT ROBOTIC INSPECTION CAPABILITIES AND CONCEPTS OF FUTURE ROBOTIC TANKSHIP INSPECTION SYSTEMS

While current robotic technology is not adequate for most tankship inspection tasks, further development of robotic inspection systems may be of great benefit in this challenging area. Improvements are needed in two main areas. First, light weight deployment systems capable of handling the long reaches and the minimal access openings are required. Second, visual inspections systems capable of detecting the full range of potential tankship defects and damage need to be demonstrated. Following is a discussion of deployment and vision system options, along with a discussion of operator interface issues and a concept for a possible robotic tankship inspection system.

5.1 DEPLOYMENT SYSTEMS

Long reach manipulator type inspections systems are preferable to remote vehicle-based systems, especially for visual inspection tasks. While remote vehicles such as submersibles, crawlers or climbers have advantages in size and range of surface accessibility, the advantages of long reach manipulator type deployment systems are more numerous. Long reach manipulator-based inspection systems, while larger, are less complex, have better operator interfaces, provide a faster inspection rate and are more cost effective.

Of the various remote vehicle options, submersibles would seem better suited to visual inspections, while crawlers or climbers might handle weld inspection or wall thickness measurement tasks better. Submersibles would be able to provide close-up inspections of most in-tank surfaces, as well as wall thickness measurements as was demonstrated with ARTIS. If used with water- filled tanks, the safety issues related to explosive gases are minimized. Inspections could be carried out at sea. An additional possibility would be to use a submersible that is used in a crude oil-filled tank. While a conventional vision system could not be used, an ultrasonically-based imaging system may be possible. While the author knows of no such system for use in crude oil, a similar system was developed to work in liquid sodium.

One drawback of a submersible inspection system is that the required distance between the submersible and the surface being inspected must be fairly close due to loss of image quality caused by viewing through extended distances of water. This prevents the ability to do a relatively quick, overall inspection to identify potential problem areas. All areas must be inspected with the same level of resolution.

A concern with remote vehicle-based inspection systems is in keeping track of the exact location being inspected and being sure that all desired surfaces are inspected. These problems might be overcome with improvements in vehicle position sensing systems and computer interfaces.

Remote vehicle-based inspections will be relatively slow. If inspections are carried out in dry dock, this could result in unacceptable inspection times. However, if the inspections could be carried out while the vessel is underway, the time factor may not be as important.

Current concepts for remote vehicle-based inspection systems applicable to tankships require a considerable amount of operator interaction for vehicle guidance. While improvements are being made in autonomous operation, this is currently an area that detracts from their desirability.

Remote inspection vehicles applicable to tankship inspections currently require a tether for power and data transmission. Data transmission could possibly be handled by telemetry links, but a tether is still required to provide the amount and duration of power for inspecting the large volumes in a tank. Tethers inside a tank pose a real potential for becoming entangled.

One possible solution is a long reach manipulator-based robotic inspection system that would access the tank through hatches in the deck. Due to the limited access available, the most logical choice is to deploy through the Butterworth hatches. If these do not provide adequate access, additional, specially installed hatches strategically located may have to be added to the deck. To provide a reasonable amount of surface coverage while limiting the size and weight of the inspection system, a hatch will be required in each bay of each tank. The system will have to be moved to another hatch to inspect another bay.

For general condition visual inspections, it may be adequate to have the video camera and lights deployed vertically directly below the hatch. A camera with a zoom lens and lights mounted on a pan and tilt head and lowered into the tank could provide coverage of most of the inside surface of tank. Coverage of all surfaces would not be possible, but the deployment system could be as simple as a set of cables magnetically attached to the tank bottom or perhaps a stowable mast. A stowable mast is basically a preformed strip of metal that can be unwound from a spool for deployment and rewound to retrieve. A telescoping mast is also a possibility. While no detailed analysis has been performed, up to ninety percent of the side wall and side wall longitudinal surface area could be visible with a system deployed only vertically below the Butterworth hatches. The amount of surface area visible for deck and bottom members would be less, though no estimate has been made. One concern for all types of inspection systems which use a long focal length zoom lens and a relatively limber deployment system is camera movement. This is one area where use of a still video camera, possibly in conjunction with a flash unit, might improve image quality while reducing power requirements.

For close up visual inspections, it will be necessary to access both sides of most members. This will not be possible with a system that deploys only directly below the hatches. Therefore, a long reach manipulator system capable of more complete surface coverage will require lateral reach capability. The maximum reach required has not been determined accurately. However, the maximum horizontal distance from the Butterworth hatches to a tank surface appears to be

approximately 30 to 35 ft. This is the maximum lateral distance a manipulator arm would be required to reach to provide line-of-sight access to almost any surface with modest stand-off distances. There are two significant design considerations imposed by the requirement for lateral deployment of the video system. First, the deployment system must be much stronger to position the camera. In order to span the relatively large horizontal distances, the arm or other mechanism will have to be large just to support its own weight. The weight of the camera and lights or flash unit will be an almost negligible part of the total weight. The second significant design consideration is that the deployment system must be prevented from colliding with the tank structures and damaging the tank and/or the inspection system. Since the operator will not, in general, be able to watch the manipulator in action, some type of automatic collision prevention strategy will have to be developed. A strategy will have to be developed for scanning the structure most efficiently while working with the collision avoidance system.

One method that might be used to advantage is to brace the deployment system against the inside of the tank, either at the bottom or side wall. The deployment system could be magnetically or otherwise temporarily attached to the surface at one of the intermediate joints. This would significantly increase the rigidity of the system and potentially simplify the collision avoidance procedures. This approach could also increase the complexity of the operation. If ultrasonic wall thickness measurements are to be made using a long reach manipulator or similar mechanism, bracing will almost certainly be required. It may be very advantageous to adopt a bracing strategy, when one considers the requirements to keep the inspection system man-portable. Without using intermediate bracing, the system's weight would be much higher.

5.2 VISION SYSTEMS

Any consideration of a video-based vision system must include both the camera and the required lighting. Of the two, the lighting may be the most problematic for tankship inspections. The volumes to be inspected are huge and the surface less than ideal. Also, the use of high intensity lights or strobes, in conjunction with the potentially explosive environments of the tanks, will require the use of special equipment. The most convenient location for mounting the lighting is next to the camera, probably on the same pan and tilt head. However, this may limit the depth perception qualities of the video image. An alternate mounting arrangement might be required.

The state-of-the-art in both motion and still video cameras appears to be adequate for this inspection task. High resolution black and white cameras are readily available. Some cameras that use intensified imagers, such as those used for very high-speed video recording, can operate under very low light conditions. While these cameras would still require the use of lights in the tank, the intensity of the lights could be much less than for more conventional cameras. The resolution capability of color cameras is not as good as that for black and white cameras. However, their use may be beneficial because of the additional information contained in the image. The use of a color camera in combination with a higher

resolution black and white camera might be a good alternative. It might also be advantageous to combine lower resolution motion video camera with a higher resolution still video camera.

The biggest interaction of the requirements of the deployment system and the video system will be in the stability of the video image. All of the manipulator-based deployment systems that have been considered will be relatively limber and have very low natural frequencies and have low damping. After the deployment system has been moved or the pan and tilt mechanism actuated, it may require a very long time for the system's amplitude of vibration to become acceptable unless a bracing strategy is used. The use of a still video camera and a high intensity strobe may be required to overcome this problem. This may limit the speed of inspection.

An alternative to video-based vision systems that merits further investigation is laser-based devices. A laser range finder is a device that can provide images to the operator that are analogous to video images. A laser light is scanned over the surface, reflected back to a sensor and both distance and reflected intensity data is recorded. The distance data has the potential to be used to generate three-dimensional maps of the visible surfaces. The reflected intensity data might be used as a substitute for black and white video image. The use of laser range finders for use in characterizing large, underground, waste storage tanks is currently being explored. This inspection task has some similarities to the inspection of tankship tanks. The results to date have been mixed because this is still a developing technology. Improvements in laser range finder technology may make this a more viable alternative.

5.3 OPERATOR INTERFACES

Operator interfaces are of two types. The first are those that permit the operator to control the system, position the vision system, and scan the interior of the tank. The second are those that let the operator "see" the internal surfaces of the tank. Both of these interface types must be developed correctly in order to have a useable system.

Robotic systems can be operated in two modes. The simplest is telerobotically, in which the operator controls the system in a master/slave manner, usually with a mechanical input device. The other mode is fully automatic control, where the computer system follows a preplanned motion sequence possibly with input from sensors. These preplanned motions could be from a previously recorded telerobotic inspection or based on a mathematical model of the tank and inspection system. A combination of these two modes uses supervisory control by the control system to prevent an operator from violating certain constraints. This might be used to prevent the operator from inadvertently hitting the tank wall with the inspection system. Control of the system requires consideration of how fast the operator can interpret the visual images, the quality of the image, the field-of-view, the response characteristics of the system, the concerns for collision avoidance, and the details required by the inspection. With a more automated control system, the operator can pay more attention to the visual images. The interface between the

operator and the inspection system must permit the operator to select a particular location inside the tank and move the inspection system to view the selected location. For every image on the monitor, the operator must also be able to determine the image's corresponding location in the tank. Since the visual images will be stored for future reference, it must be able to readily return to the stored data and select an image or images of a desired location based on an easy to understand reference system. Data management will be a significant consideration in how the images are stored. If the system is used to take wall thickness measurements, the operator must be able to place the ultrasonic probe on the surface in any desired location.

The most critical part of the inspection system will be the operator. Due to the complex nature of the inspection task, the detection of defects will be almost solely accomplished by the operator while viewing an image on a monitor. For an acceptable inspection, the images on the monitor must be of high enough quality and resolution to permit the detection of defects. How the image changes over time on the monitor will also be important. If there is oscillatory motion caused by vibration of the system, the operator will not be able to watch the monitor for very long without discomfort. Images must also not move too quickly across the monitor, or defects may not be detected. A key determining factor in the viability of a robotic inspection system will be in how long an inspector will be able to effectively and reliably use the system.

5.4 CONCEPT FOR A POSSIBLE ROBOTIC TANKSHIP INSPECTION SYSTEM

Due to the benefits to be gained in improved cost effectiveness and increased safety of tankship inspections, robotic or at least remote inspection systems will continue to be developed. While there would have to be substantial advances in many different technology areas before the need for man-in-the-tank inspections could be eliminated, robotic inspection systems can currently be developed to aid and improve the inspection process. The maturation of robotic inspection technology and the experience gained with initial tankship inspection systems will permit the development of better equipment and techniques. If the goal of a robotic inspection system that meets the requirements outlined in the performance specifications section is to be reached, an evolutionary path will have to be taken. One concept of how tankship inspections might evolve is described below.

Based on the access constraints, a system that can be deployed through the Butterworth hatches will be used. In fact, the NETSCO system may be first step in this direction. The system will initially be used to augment the current general visual inspection. The inspection system will use a combination of both color and high resolution black and white motion video cameras. Lights will be selected to provide adequate illumination and be safe to operate in the potentially explosive environment. The tank surfaces will have to be cleaned to the same levels as is currently required for man-in-the-tank inspections. The atmosphere in the tank will also have to be maintained as non-explosive. For this generation of the inspection system, the video equipment will be deployed directly below the Butterworth hatch. It is expected that the deployment system will be a telescoping mast or a stowable mast. The video equipment will be

attached to a pan and tilt head on the lower end of the mast. The mast will have the capability to position the video equipment approximately 75 ft. below deck level. The operator will control the inspection system in a telerobotic manner, at least initially. The operator will be able to control the extension of the mast below deck level and the pan and tilt angles of the cameras. The zoom lenses on the cameras will also be controllable. The system may also be capable of simple automatic, robotic scanning. This could use either taught inspection paths or simple preplanned paths. The visual information will be displayed on a pair of monitors at the operator control station, which will be on deck near the access hatch. The video signals will also be recorded on magnetic tape along with time stamps, location data and possible voice annotation by the operator.

This first generation inspection system will be most useful in providing improved visual access to some under deck structures and the majority of the side walls. It will also permit the assessment of the capabilities of an inspector to detect defects from video images. Until actual images from the inspection system are available, an accurate assessment of the adequacy of the image quality will not be possible. It is probable that only a single copy of the first system will be built and used primarily as a exploratory tool. Once the abilities of the system are demonstrated, the system could be used to refine the requirements for this type of inspection equipment.

Much will be learned from the deployment of this first generation system. While the design challenges for this first generation system are less than those for a more complete system, they will still be formidable. All of the issues related to safe operation of an inspection system on a crude carrying vessel will have to be addressed. Of particular concern will be the lights and other electrical components. The source of operating power will also be a design concern. Operational experience will result in the ability to make design refinements to this first generation inspection system. The biggest improvements to be made may be in the user interfaces. This is the area where operation under actual field conditions will provide the best basis for design improvements.

Continued use of the inspection systems would result in the continual evolution of the design. At some point, the ability to do wall thickness measurements would be added to the system or a separate system developed for that purpose. The ultimate goal would be to eliminate the need for the man-in-the-tank operations, while meeting the performance requirements outlined earlier in this report.

6.0 CONCLUSIONS AND SUMMARY

Current tankship inspection techniques are manual, time consuming, dangerous and generally not thorough due to the constraints imposed by the limited time available for inspections and the immense volumes that must be inspected.

Robotic inspection techniques are only just beginning to be used for tankship inspections.

Robotic inspection systems have the potential to lead to more cost effective inspections, while improving the quality of the inspections. However, significant technology development and testing must occur before the inspection of tankship tanks can be carried out completely with robotic/remote inspection systems. Many parts of the inspections will still have to be done with a man in the tank for the foreseeable future. Considerable progress will be required in the development of deployment systems, vision systems, operator interfaces and long reach manipulator stability before a robotic tankship inspection system can be produced that is viable for routine use.

However, much benefit could be gained if even a limited portion of a tank inspection could be done with robotic/remote inspection equipment. The development of limited scope, remote visual inspection equipment to augment the current general condition inspections appears to be viable and realistic. The true potential benefits of robotic/remote technology to tankship inspections can not be determined until at least some real-life experience is obtained. Technology is advancing rapidly and the application to tankship inspections should be continually investigated.